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DESIGN, SIMULATION AND IMPLEMENTATION OF A 60KW VARIABLE VOLTAGE DC POWER SUPPLY FOR A CURRENT-FED PARALLEL RESONANT INVERTER USED IN INDUCTION HEATING APPLICATIONS

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Abstract: This research deals with the design, simulation and Implementation of a 60kW variable voltage, current source, DC power supply suitable for induction heating purposes composed of three-phase fully controlled full-wave rectifier (3-Ph FCFWR) with a smoothing reactor. It is suitable to supply a current-fed parallel inverter (CFPI) frequency converter (built on Transistors), feeding a high quality factor resonating induction heating load. Such a source must verify two main objectives for achieving safety start up, those are: (a) achieving an aperiodic dynamic behavior during starting, since it may result in overvoltage across different elements of the converter, (b) assuring continuous current mode operation to achieve safety start up. A high inductance smoothing reactor is usually connected with the input of the inverter to perform these objectives. In this research the theoretical derivation is modified to reach the suitable formula to determine the value of the self-inductance of the smoothing reactor for the required power supply. Also, the smoothing reactor is designed and implemented. The designed power supply is simulated using (MATLAB) package. The practical measurements of load voltage and current waveforms at the starting angle of the implemented power supply satisfying the above two main objectives and are in a good agreement with the simulated waveforms at that angle.

Keywords: *continuous-current mode, induction heating, smoothing reactor.*

تصميم ومحاكاة وتنفيذ مجهز قدرة تيار مستمر60KWمتغير الفولتية خاص بالعاكسات المغذية للمسخنات الحثية برنين التوازي وتطبيقاتها

الخلاصة:أن هذا البحث يهتم بتصميم و نمذجة و تنفيذ مجهز قدرة تيار مستمر بقدرة 60 كيلو واط متغير الفولتية يعمل كمصدر تيار مناسب لأغراض التسخين الحثي. يتكون هذا المجهز من معدل موجة كاملة ثلاثي الطور و من مفاعل تنعيم. أن هذا المجهز مناسب لتغذية عاكس تبديل التردد المتوازي المغذى بالتيار(المكون من ترانزستورات)، أن حمل هذا العاكس هو فرن تسخين حثي رنيني (أي يعمل في حالة رنين دائما) يتصف بمعامل نوعية عالي. أن مثل هكذا مصدر للقدرة يجب أن يؤمن غايتان لتحقيق بدء آمن لمنظومة التسخين الحثي هما: (أ) الحصول على تصرف ديناميكي لا دوري خلال عملية بدأ التشغيل، إذ أن عدم الحصول على مثل هذا التصرف سيؤدي الى نشوء فولتيات عالية عبر مكونات المبدل خارج حدود إمكانياتها. (ب) الحصول على حالة تيار لا يصل الى قيمة الصفر عند البدأ لتحقيق سلامة المنظومة. إن تأمين الغايتان أعلآه يتم من خلال ربط ملف تنعيم ذو محاثة عالية عند مدخل العاكس. في هذا البحث تم تطوير الأشتقاق النظري للتوصل الى صيغة مناسبة لتحديد قيمة الحث الذاتي لملف التنعيم لمجهز القدرة المطلوب، كما تم تصميم و تنفيذ ملف التنعيم. تم أستخدام برنامج (ماتلاب) لتمثيل مجهز القدرة الذي تم تصميمه. أظهرت القياسات العملية للأشكال الموجية لفولتية و تيار الحمل من مجهز القدرة المنفذ عند زاوية القدح الخاصة بالبدأ، تأمين الغرضين أعلآه، كما أظهرت التقارب الكبير مع الأشكال الموجية المستحصلة من التمثيل الرياضي عند هذه الزاوية.

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1. Introduction

The need arises for a medium power, variable voltage, current source, DC power supply in research and development (R&D) laboratory suitable for induction heating research work. Such a supply composed of a three-phase fully controlled full wave rectifier (3-Ph FCFWR) and a smoothing reactor. The expected load of this rectifieris a thyristorized single-phase frequency converter that widely used in industry as medium-frequency (1–100 kHz) and medium-power (1–1000kW) supplies induction metal melting and heating installations.

In order to design a DC power supply being compatible to feed such a load, a smoothing reactor must be carefully designed to achieve a current source operating in continuous-current mode and has a non-oscillatory (aperiodic) dynamic response during starting. The previous works [1, 2] determine the suitable approximate value of such a smoothing reactor, using thyristorized single-phase frequency converter. Figure (1) represents the thyristorized power supply with its load.

The principle of operation of the Thyristor Controlled Rectifier (TCR) is already known, and its output voltage waveform is a function of the triggering angle (the controlled angle) (α). The controlled angle α may be changed in the interval$(\pi/3 < \alpha < 2\pi\ /\ 3)$, while the discontinuous mode of operation might only be when $\alpha > 2\pi/3$. The discontinuous mode of current operation leads to unsafe starting of the CFPI. Shenkman (2000) determines a mathematical formula related to system elements and parameters to avoid this discontinuity [2].The transient analysis during starting shows the dependency of the smoothing reactor value on the starting up current transient response, in that it may be an aperiodic, critical, or oscillatory. The periodic or oscillatory operation mode is undesirable because, it may result in overvoltage across different elements of the converter. To achieve a non-oscillatory transient current response. Shenkman (2001), suggests another formula for this purpose [1]. Hence, the two formulae are calculated and the highest value is recommended to be used.

This research deal with the design of a transistorized inverter instead of the thyristorized one. The two formulae suggested by Shenkman, modified to determine the required value of the self-inductance of the smoothing reactor to achieve a non-oscillatory transient current response and assuring continuous current mode operation to achieve safety start up.

This work interested also in the design of the smoothing reactor. The standard (B-H) curve of the magnetic material used as a core for the smoothing coil implemented in the Diala State Company for Electrical Industries is considered to determine all the required parameters of the coil magnetic circuit.

A (MATLAB) package was used to design and simulation of the power supply. The designed controlled rectifier with its smoothing reactor was implemented to perform 513V, 117A, 60kW variable DC voltage source. The experimental work shows that the waveforms of the starting voltage and current are in good agreement with that determined by the simulation, so the required starting conditions are well verified.

2. Theoretical Background

In order to be able to determine the magnitude of the self-inductance of the smoothing reactor, the literature deals with this subject must be studied carefully in order to apply it in the required induction heating power supply. The (3-Ph FCFWR) is widely used in induction heating supply units. Then its operation must be declared here in order to make it possible to design the smoothing reactor (L_d). Fig. (1), shows the (3-Ph FCFWR) normally associated with its load. The analysis of this circuit is simplified by replacing the model of the inverter which contains switches by a switchless circuit of the second order which is shown in Fig. (2), whose parameters (L_d, R_e)are chosen in such a way that the circuit approximates the real inverter shown in Fig. (1).

The controlled angle α may be changed in the interval $(\pi/3) < \alpha < (2\pi/3)$, while the discontinuous mode of operation might only be when $\alpha > (2\pi/3)$. The voltage waveform in this case is shown in Fig. (3), it is evident that the current waveform in the corresponding instant will be discontinuous. The theoretical background of the Thyrestorized power supply shown in Appendix-A.

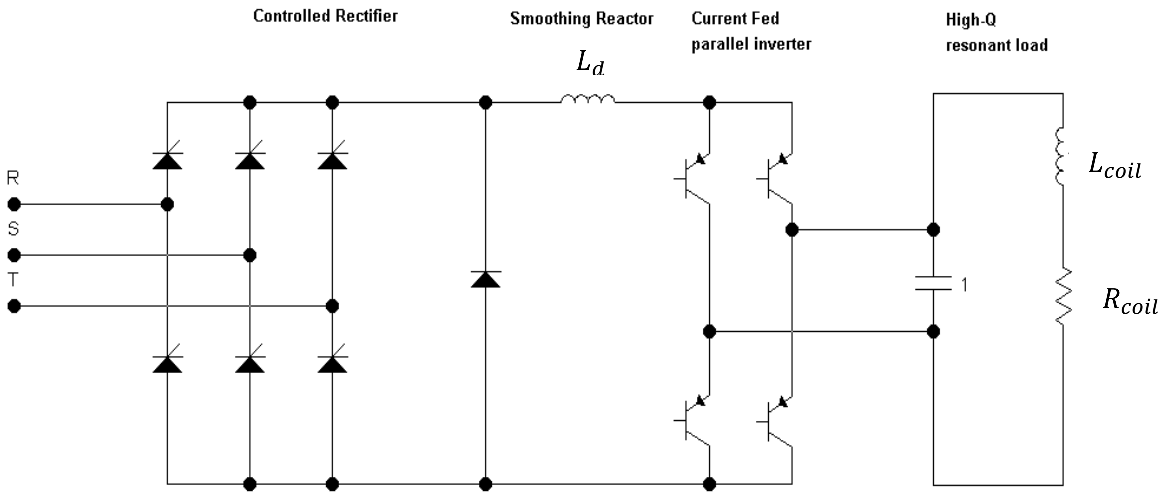


Fig. (1) The DC power supply to be designed

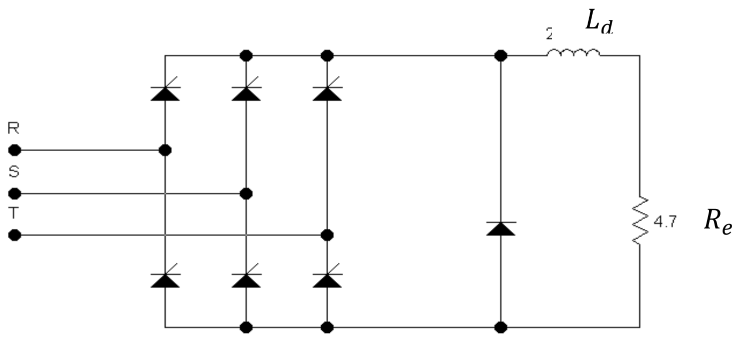


Fig. (2) The Thyristor Controlled Rectifier (TCR).

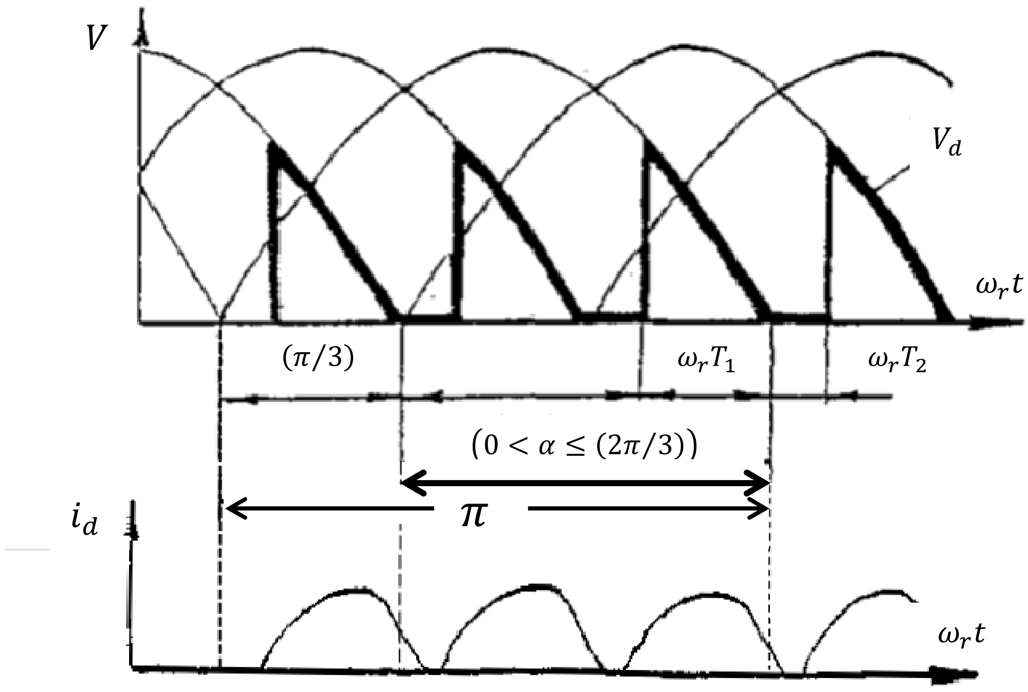


Fig. (3) The voltage and current waveforms at the discontinuous mode(α=95˘)

3. Design Equation of a smoothing reactor using MOSFETs inverter:

The design equations in Appendix-A are derived especially for Thyristor Frequency Converter (TFC), but in this work the single-phase inverter uses MOSFETs, as shown in Figure (1). This will make a little bit change that must be considered in applying these equations.

Due to the above requirements and limitations, these equations have to be changed to describe the characteristics of the required power supply as follows:

The maximum value of the rectified output voltage$(V_{d_{max}})$, due to the equation (A-10) at α = 0.0^o, is:

$$V_{d_{max}} = \frac{3\sqrt{2}}{\pi} V_r = 1.35 \times 380 = 513.18\text{V}$$

The minimum value of the rectified output voltage$(V_{d_{min}})$, at α = 94^o, assume $(D = 10)$ is:

$$V_{d_{min}} = \left(\frac{3}{\pi}\right) V_{r.m}[1 + cos(\pi/3 + \alpha)] = 54.756V$$

Since the inverter uses transistors and supplying a resonating load, then the expected value of the shift angle(β), between voltage and current for the inverter output in the range$(0^{\circ} \leq \beta \leq 5^{\circ})$, hence$(1 \leq cos\beta \leq 0.996)$. This property leads to consider the voltage factor due to the equation (A-4)

$$K_V = \frac{V}{V_d} = \frac{\pi}{2\sqrt{2} \times cos\beta}$$

$$(1.11 \leq K_V \leq 1.114)$$

This result affects the equation (1), in that the factor$\sqrt{8K_V^2 - \pi^2} \approx 0.0$, then the equation (A-1) reduced to

$$L_d = \frac{5V_d^2(Q\pi)}{\pi^2 P f K_V^2}$$

Or

$$L_d = \frac{5V_d^2 \frac{2\pi^2 f L_C}{R_C}}{\pi^2 P f K_V^2} = \frac{10V_d^2 L_C}{P R_C K_V^2}$$

Since,$(P = V_d^2/R_C)$ then

$$L_d = \frac{10L_C}{K_V^2}(1)$$

L_C : Equivalent inductance of the furnace induction coil.
R_C: Equivalent resistance of the furnace induction coil.
Then, if the average value of the voltage factor $K_V \cong 1.112$, then by substitution of these values in the above equation (1) results in:

$$L_d = \frac{10\ L_C}{(1.112)^2} = 8.87 \times L_c(2)$$

Note: This equation leads to conclude that the value of(L_d), is independent on the inverter frequency or power, but the above derivation assumes a high quality factor load for the resonating circuit of magnitude$(Q = (10 - 20))$, which is a function of inverter frequency, so the load identification is very important in order to decide whether the above calculations are valid or not.
To deal with the second period $(\omega_r T_1 < \omega_r t \leq \omega_r T_2)$ described by equation (A-7) to achieve an aperiodic dynamic behavior during starting, substitute the value of L_d described by (2) in (A-7) results in

$$i_d = I_{st} e^{-(R_e/L_d)t} = I_{st} e^{-(R_C/(8.87L_C)t}$$

But the average value of starting current at this period $I_{st} = (V_{d.min}/R_C)$. Then the expected current at $(t = 3\tau = 3\text{ms})$ is

$$i_d = (V_{d.min}/R_C) \times e^{-[R_C/(8.87L_C)]\times(3\times10^{-3})}\ (3)$$

4. Design calculations of the smoothing reactor

Due to the previous analysis($V_{d.max} = 513.18V$) and since the required power is($P = 60\text{ kW}$). Now, assume the quality factor of the load=20, and the resonating frequency is (70 kHz), then for the load parameters($L_c = 0.19943$mH) [2], and ($R_C = 4.386\Omega$)

$$Q = \frac{2\pi \times 7 \times 10^4 \times (0.19943) \times 10^{-3}}{4.386} = 20$$

Then

$$L_d = 8.87 \times L_C = 8.87 \times 0.00019943 = 0.001769 = 1.77\text{mH}$$

To check the aperiodic dynamic behavior during starting condition, substitute the designed values at equation (19) yields to

$$i_d = \left(\frac{54.756}{4.386}\right) \times e^{-\left[\frac{4.386}{0.00177}\right] \times (0.003)} = 7.4\text{mA}$$

Note: For constant quality factor the self-inductance of the smoothing reactor will be a function of the inverter frequency, because $L_C = \frac{QR_C}{2\pi f}$and($L_d = 8.87 \times L_C$).

$$L_d = 8.87 \times \frac{QR_C}{2\pi f}$$

Since, the nature of the induction heating load is that; the values of (R_C, L_C, f and Q), are variables during the heating process, so it is better to design the smoothing reactor to be of inductance greater than that calculated due to (2) in order to work safely. Also, this discussion leads to believe the truth that, "the inductance and the quality factor of each induction heating load must be defined before being fed from any current source power supply to check its compatibility".

The value of the self-inductance of the smoothing reactor (L_d)in this research determined to be greater than the calculated one due to (2), and considered to be($L_d \cong 10 \times L_C = 2$mH). This leads to achieve ($i_d = 17.3$mA), instead of (7.4mA). Hence, the designed value assures the continuity of current during the starting process.

5. Experimental Measurement of ($L_C, R_C, f,$ and Q), for an induction coil:

It is already known that the application determines the required frequency in the induction heating process[5]. Hence, the parallel capacitor(C_R), connected to the induction coil (tank circuit) must be determined such that the resonance frequency of the tank circuit must be the required frequency suitable for that application. The coil resistance can be determined using any conventional method used for resistance determination. This arrangement can be satisfied in spite of the unknown induction coil inductance and the tank circuit quality factor by the most accurate method suitable to study the parameters($L_C$and Q), for any induction coil experimentally. This is done by applying a pulse of suitable voltage amplitude to the tank circuit composed of a certain defined capacitor(C_R), connected in parallel to the induction oil.

The obtained frequency of the oscillating current can be determined. The value of the tank capacitor can be changed in order to achieve the required frequency for that application. Then the self-inductance of the induction coil can be determined using the resonant frequency formula [6]

$$f = \sqrt{\left(\frac{1}{L_C C_R} - \frac{R_C^2}{L_C^2}\right)} \quad (4)$$

This leads to determine the quality factor also. The commercial measuring device used for this purpose is known as (Load Frequency Analyzer) [4].

6. Design of the smoothing reactor:

Since any smoothing reactor is connected in series between the source and load terminals, then the total load current will pass through it, hence it suffers from saturation in addition of its inherent nonlinearity in its magnetic core characteristics. These two difficulties can be avoided by making an air-gap in its magnetic circuit. So, in general, for any smoothing reactor there is an air-gap.

It is already known that the magnetic circuit equation is$[\varphi = (NI/S)]$, where ($\varphi \equiv$ the magnetic flux (Wb),$N \equiv$ the number of turns of the coil, $I \equiv$ the current passing through coil turns and $S \equiv$ the magnetic reluctance (A.Wb^{-1}). The total magnetic reluctance(S_T), in this case, two terms one of iron(S_i), and the other of the air-gap$\left(S_g\right)$, as$\left(S_T = S_i + S_g\right)$ will be composed. But since,$\left(S_g \gg S_i\right)$, then $\left(S_T \cong S_g\right)$, this leads to $\left[\varphi = \left(NI/S_g\right)\right]$ in an air-gapped coil. Now, in order to overcome the non-linearity and to work in the easy magnetization region of the (*B*-*H*) curve of the core material the maximum value of the excitation current must be considered such that it will not exceed the linear part, then:

$$\varphi_{max} = \frac{NI_{max}}{S_g} \quad (5)$$

But($\varphi_{max} = B_{max} \times A_c$), where $B_{max} \equiv$ the maximum flux density (Wb.m^{-2}), and $A_c \equiv$the iron core cross-sectional area (m^2). Then

$$B_{max} A_c = \frac{NI_{max}}{S_g} \quad (6)$$

Or

$$NI_{max} = B_{max} A_c S_g \quad (7)$$

Since$\left[S_g = l_g/(\mu_o A_c)\right]$ then

$$A_c S_g = \frac{l_g}{\mu_o} \quad (8)$$

$l_g \equiv$ The air-gap length (m),
$\mu_o \equiv$ The permeability of air-gap (H.m^{-1})
Substitute (8) in (7) results in

$$NI_{max} = B_{max}\frac{l_g}{\mu_o} \quad (9)$$

Since, the inductance of the smoothing reactor has been$\left(L_d = N^2/S_g\right)$, this leads to[7]:

$$L_d = \frac{\mu_o N^2 A_c}{l_g} \quad (10)$$

Then $l_g = \frac{\mu_o N^2 A_c}{L_d}$(11)

From (9) $N = \frac{B_{max} l_g}{I_{max}\mu_o}$, and this equation can be written as$\left(N^2 = \frac{B_{max}^2 l_g^2}{I_{max}^2 \mu_o^2}\right)$. Substitute in (11) for(N^2), results in:

$$l_g = \frac{\mu_o L_d}{A_c} \times \frac{I_{max}^2}{B_{max}^2} \quad (12)$$

Or

$$\frac{l_g}{\mu_o} = \frac{L_d}{A_c} \times \frac{I_{max}^2}{B_{max}^2} \quad (13)$$

Substitute (13) into (9) results in [7]

$$N = \frac{L_d}{A_c} \times \frac{I_{max}}{B_{max}} \quad (14)$$

7. Design procedure

As mentioned before, the required smoothing reactor to be designed must be of (2mH) self-inductance and (117A) in order to feed (60kW) load. The available steel sheet is of type G8 due to the Japanese Industrial Standard (JIS) its DC magnetization curve is shown in Fig. (4) The characteristic is linear up to about ($B \cong$ 1.1T), hence, let us consider($B_{max} = 0.85$T), ($I_{max} = 117$A) and$\left(l_g = 3.2\text{ mm}\right)$, due to the available insulating material to be used in the air-gap region. To determine(A_c), apply equation (15) results in

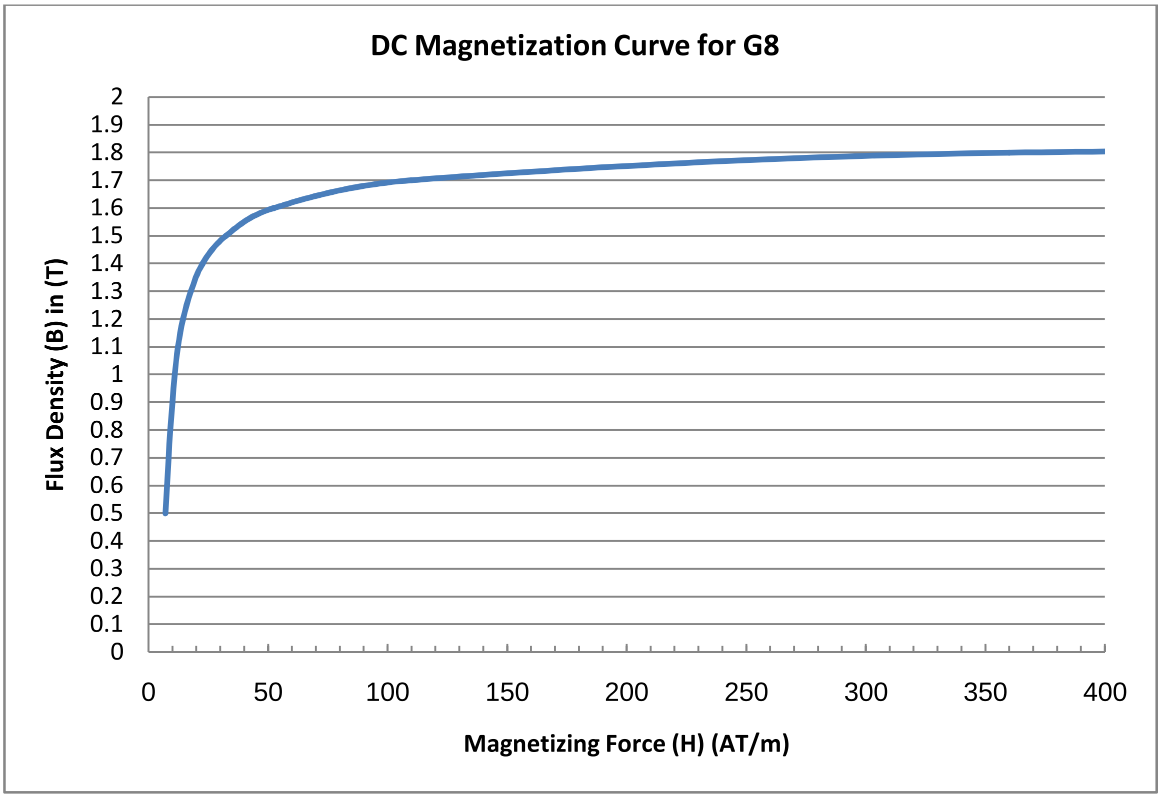


Fig. (4) The DC magnetization Curve for magnetic steel sheet type G8 due to the Japanese Industrial Standard (JIS)

$$A_c = \frac{\mu_o L_d I_{max}^2}{B_{max}^2 l_g} \quad (15)$$

$$A_c = \frac{4\pi \times 10^{-7} \times 2 \times 10^{-3} \times (117)^2}{(0.85)^2 \times 3.2 \times 10^{-3}} = 148807.1 \times 10^{-7}\mathrm{m}^2 = 148.8\ \mathrm{cm}^2$$

Since this value of the core area is too large, then another area of($A_c = 95\mathrm{cm}^2$)can be considered. Now, recalculate ($B_{\max}$) for ($A_c = 95\mathrm{cm}^2$) using (31) also, which leads to:

$$B_{max}^2 = \frac{\mu_o L_d I_{max}^2}{A_c l_g} = \frac{4\pi \times 10^{-7} \times 2 \times 10^{-3} \times (117)^2}{95 \times 10^{-4} \times 3.2 \times 10^{-3}}$$

$$B_{max} = 1\mathrm{T}$$

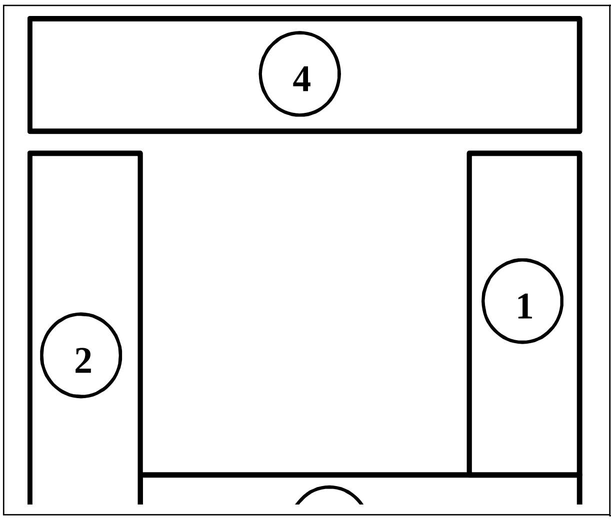
This value can be applied safely because it is within the linear region of the (B-H) curve of the iron core material. Now to find the number of turns use equation (30):

$$N = \frac{2 \times 10^{-3}}{95 \times 10^{-4}} \times \frac{117}{1} = 24.6$$

Then the number of turns considered in this design is (N=24). To choose the suitable wire gauge, considering the current density (J)on the wire to be ($5\mathrm{Amm}^2$), then $J = \frac{I_{max}}{A_W}$, $A_W \equiv$ the copper wire cross-sectional area (m^{-2}), so,

$$A_W = \frac{117}{5} = 23.4\text{mm}^2$$

The closest standard wire for this value is a fiberglass insulated copper wire of dimensions (3.5 × 6.2) mm is the most suitable for this design. Figure (6-a) shows the core lamination arrangement and Table (1) show their dimensions, while Figure (5-b) represents the already designed and manufactured coil.



(5-a) Core lamination (5-b) The designed coil

Figure (5) Designed and manufactured smoothing reactor

Table (1) Core Lamination Dimensions

Item	*Dimension of pieces (mm)*	*No. of pieces*
1	95 × 160	335
2	95 × 255	335
3	95 × 135	335
4	95 × 230	335

The total dimensions of the designed coil are:

$l_{gl} \equiv$ The air-gap per one limb=1.6mm. $l_g = 2 \times l_{gl} = 2 \times 1.6 = 3.2\text{mm}.$

Thickness of each lamina= 0.3mm Gross width=335 $\times$ 0.3=103.1mm

Stacking Factor= 0.97 Core Net Area = 95 $\times$ 103.1 $\times$ 10^{-6} $\times$ 0.97= 0.0095 m^2

Core mean length (l_c)= 255+135+255+135= 780mm

Hence, $(H_{max} = NI_{max}/l_c) = \left(24 \times \frac{117}{0.78}\right) = 4615\text{Am}^{-1}$ and this value will initiate one tesla flux density in the designed core. So, the operation is in the linear region.

8. Simulation and Practical Results

The power supply was designed and simulated using MATLAB-Simulink computer package. Fig. (6) shows the MATLAB-Simulink connection diagram of the power supply, while figures (8, 9) show the simulated voltage and current waveforms at (α=95°).

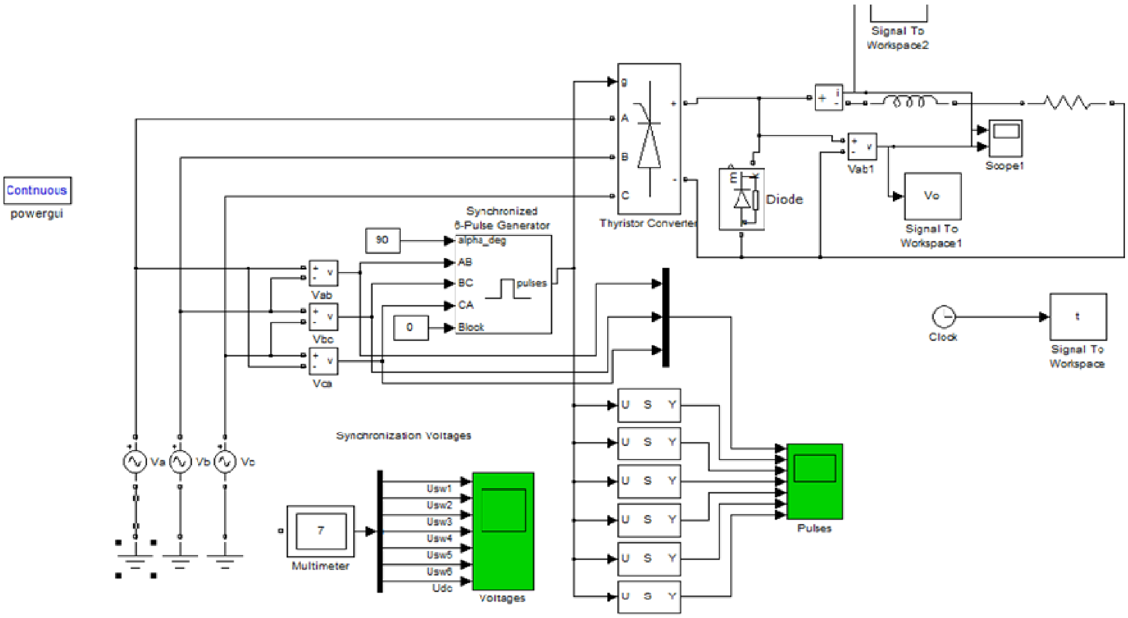


Fig. (6) The MATLAB-Simulink connection diagram

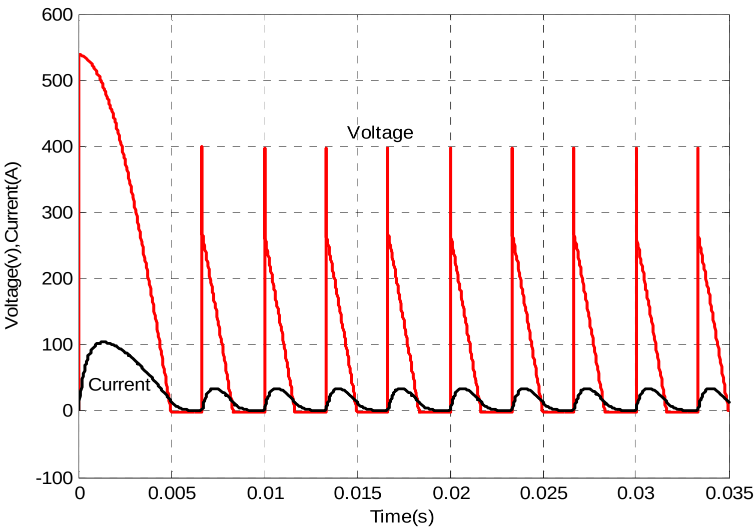


Fig. (7) The voltage and current waveforms at(α=95°).

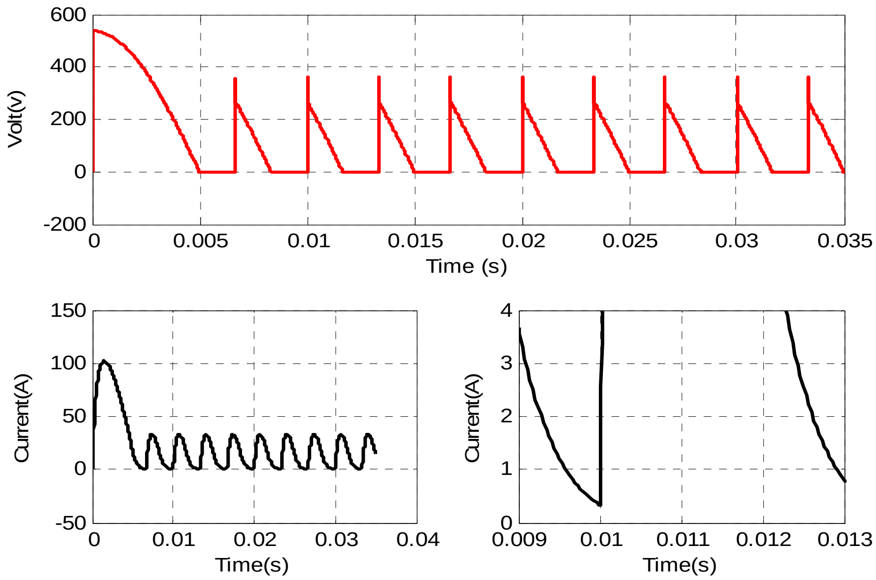


Fig. (8) The voltage and current waveforms at(α=95^0) representing the continuity of the starting current.

9. Implementation of Power Supply:

The designed power supply was implemented; Fig. (9) shows the power supply during operation. The practical results are shown in figures (10, and 11) represent the voltage and current waveforms at a starting triggering angle(α=95°). Fig. (11) shows the output voltage waveform, declares an unbalance in the applied line to line voltages during the test. Also, it shows the output current waveform passing through the load at that triggering angle. It is clear that the minimum value at the end of the transient period will never reach zero. This truth is quite clear in the fig. (11) which shows the current waveform also, but with different time and voltage scale.

Fig. (9) The power supply during operation

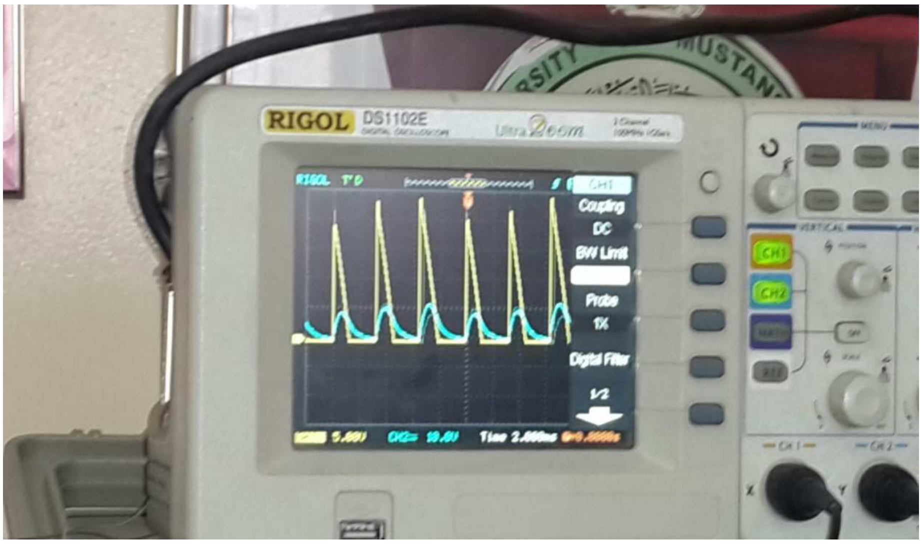


Fig. (10) The voltage and current waveforms for ($\alpha \approx 95^{\circ}$) Time scale= 2ms, Voltage scale, ch1=5V, ch2=10V

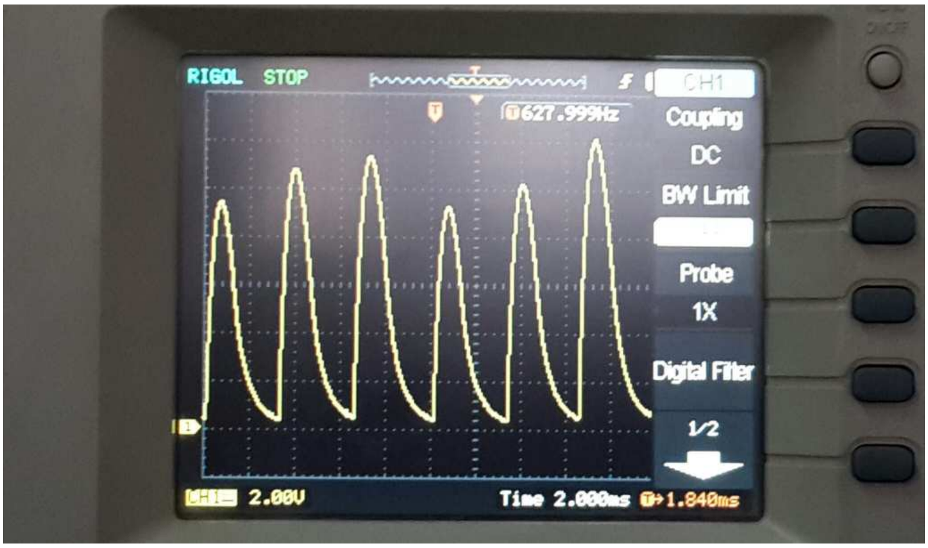


Fig. (11) The current waveform for the same triggering angle($\alpha \approx 95^{\circ}$), representing the continuity of the starting current.

The obtained practical results show a good agreement with the simulation results shown in figures (7, 8) for the same triggering angle, using (MATLAB-Simulink) simulation.

10. Discussion

The quality factor condition must be considered if the load is changed to assure aperiodic continuous current mode at starting of the induction heating furnace. This means that with this power supply since,($L_d \approx 10 \times L_C$)and $\left(R_e = \frac{V_d^2}{p}\right)$, and $[Q = (\omega L_c / R_c)]$, then these restrictions must be studied to determine the variation margin of the load parameters $(f,\ L_C,\ R_c)$. For example: if the inverter frequency is constant, then the equivalent resistance of the new load must be ($\leq R_e$) to use this power supply safely. Also, for a lower value of the operating frequency margin, the inverter is affected by the quantity$[Q = (\omega L_d/R_e) \geq 20]$. This means that in order to satisfy the above two conditions mentioned at starting, the load parameters must be studied carefully.

11. Conclusion

a- The implemented source is capable to feed a variable DC voltage (513.18 -54.756) V, the maximum power at the 513.18V case is 60kW, maximum DC current is 117A. It works as a current source feeding a single phase inverter loaded by a resonating tank circuit of effective resistance (4.386Ω), such that the quality factor greater than 20.

b- The experimental results show a good coherency with those obtained by simulation. This work reveals that the determination and the design of the smoothing reactor is the vital step of building this power supply.

References

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Appendix-A

In order to assure a desired aperiodic start up transient (dynamic behavior) during starting, the value of the self-inductance of the smoothing reactor determined due to the following equation [2]:

$$L_d = \frac{5V_d^2\left(Q\pi + \sqrt{8K_V^2 - \pi^2}\right)}{\pi^2 P f K_V^2} \quad \text{(A-1)}$$

Where:

P: the output power from the converter

V_d: The mean voltage from the controlled rectifier (V_{mean}) at ($\alpha + \frac{\pi}{3}$ = 60.0°), [means($\alpha =$ 0.0°)], and

$$V_d = V_{mean} = \frac{3}{\pi} V_{line(\max)} cos(\alpha)$$

Or,

$$V_d = \frac{3\sqrt{2}}{\pi} V_r \text{(A-2)}$$

$V_{line(max)}$: The maximum value of the three phase line to line voltage applied as input to the controlled rectifier and it is sometimes denoted as$(V_{r.m})$

(V_r) : The rms value of the line to line voltage.

Q: The quality factor of the load circuit

$$Q = \frac{\omega L_c}{R_c} \text{(A-3)}$$

K_V: The voltage ratio factor

$$K_V = \frac{V}{V_d} = \frac{\pi}{2\sqrt{2} \times cos\beta} \text{(A-4)}$$

β: The turn off angle of the thyristor

V: The rms value of the inverter output voltage

L_d: The load equivalent self-inductance

R_e: The load equivalent resistance. $(R_e = R_c)$at resonance.

ω: The angular frequency of the load voltage

$$\omega = 2\pi f \text{(A-5)}$$

f: The frequency of the inverter (load voltage frequency)

To assure continuous current mode at starting up, the current must be sustained at a value greater than the thyristor's holding current(I_h), during the period$(\omega_r T_1 \leq \omega_r t \leq \omega_r T_2)$ [Refer to figure (3)]. Shenkman, studies this condition as follows:

The current in the above circuit is shown in Fig. (3), changes in accordance with the following two expressions [1]:

1- During the first period, when$[\{(\pi/3) + \alpha\} < \omega_r t < \pi]$, as

2-

$$i_d = \frac{V_{r.m}}{z} \left[sin\left(\omega_r t + \frac{\pi}{3} + \alpha - \varphi\right) - sin\left(\frac{\pi}{3} + \alpha - \varphi\right) e^{-(R_e/L_d)t} \right] \text{(A-6)}$$

3- During the second period $(\pi \leq \omega_r t \leq \omega_r T_2)$, as

4-

$$i_d = I_{st} e^{-(R_e/L_d)t} \text{(A-7)}$$

Where:

i_d: The instantaneous value of the load current.

α:The triggering angle.

ω_r : The angular frequency of the rectifier AC supply.

φ: The phase shift angle, and is given by:

$$\varphi = tan^{-1}(\omega_r L_d/R_e) \text{ (A-8)}$$

$V_{r.m}$: The amplitude (peak or maximum value) of the line to line of the input voltage to the controlled rectifier.
I_{st}: The initial value of the current for the second period, achieved at the end of the first period.
z: The load impedance as shown in figure (2)

$$z = \sqrt{R_e^2 + (\omega_r L_d)^2}$$

The controlled rectifier output voltage (V_d) (The voltage across the freewheeling diode) depends on the maximum (peak) input line to line voltage($V_{r.m}$) , and on the thyristor triggering angle(α) , as follows:

$$V_d = \left(\frac{3}{\pi}\right) V_{r.m} \cos\alpha \qquad \left(0 < \alpha < \frac{\pi}{3}\right) \text{ (A-9)}$$

$$V_d = \left(\frac{3}{\pi}\right) V_{r.m}[1 + cos(\pi/3 + \alpha)] \qquad \left(\frac{\pi}{3} < \alpha < \frac{2\pi}{3}\right) \text{ (A-10)}$$

And if $V_{d.max}$, corresponds to $\alpha = 0$ and $V_{d.min}$, corresponds to α_{max}, we get

$$\alpha_{max} = cos^{-1}\left(\frac{1}{D} - 1\right) - \frac{\pi}{3} \text{ (A-11)}$$

The factor($D = V_{d.max}/V_{d.min}$) is the regulation range, which is usually given by the technological process. Since for most industrial equipment($5 < D < 10$), then

$$83° \le \alpha_{max} \le 94° \text{ (A-12)}$$

$$\text{And } T_2 = \big((\alpha_{max} - (\pi/3))/\omega_r\big) \text{(A-13)}$$

For $\alpha_{max} = 83^{\circ} = 1.4486$ rad, and $\omega_r = 2\pi 50 = 314.159$ rad.s^{-1}, then

$$T_2 = \big((1.4486 - (1.047))/314.159\big) = 1.277\text{ms}$$

Similarly for $\alpha_{max} = 94^{\circ} = 1.6406$ radand $T_2 = 1.88$ms.

This reveals that

$$(1.277 \le T_2 \le 1.88)\text{ms}$$

Since, the time constant of the load circuit (τ_L) lies between (0.6-1) ms, where

$$\tau_L = \frac{L_d}{R_e} \text{ (A-14)}$$

Therefore, the extended time period ($3\tau_L$) of the transient current in the second interval lies in the range between (1.8- 3) ms. This means that at the end of the second interval the current magnitude will reach not less than 5% of its value at the beginning of the interval. The condition of the continuous current mode is therefore

$$I_{end} \geq \ I_h, \text{ or } I_{end} \ \geq 20\ I_h$$

I_h : Is the thyristor holding current.
I_{end} : Is the current at the end of the first interval defined by equation (6), and
I_{st} : Is the current at the beginning of the second interval defined by equation (7), *i.e.*:

$$I_{st} = f(T_1)$$

The solution of this problem is by solving equation (6) which hasn't exact solution, but the approximate by assuming different values for R_e, and τ_L, then $I_{st} = f(T_1)$, can be determined with the aid of the curves plotted in figure (A-1). The analytical approximation of these curves might be found at

$$i_d(T_1) = \frac{0.15V_{r.m}}{R_e}\left[1 + 2\left(\frac{\pi}{2} - \alpha_{max}\right)\right]\left[1 - e^{\left(-\frac{\tau_L}{0.3\times10^{-3}}\right)}\right] \text{(A-15)}$$

Solving this equation for(τ_L), yields

$$L_d = T_1R_e \geq \left[0.3 \times 10^{-3} \times R_e \times \ln\left(\frac{0.2P\left(1+2\left(\frac{\pi}{2}-\alpha_{max}\right)\right)}{V_rI_h}\right)\right] \text{(A-16)}$$

This formula has been obtained under the assumption that the inverter operates in an aperiodic dynamic mode.The largest value of L_d obtained from (1) and (16) has to be chosen for the inverter design.